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Original
LoRaWAN Architectures in the ISM2400 Band for Agrifood Applications / Filipescu, Elena; Scatozza, Fabio; Colucci, Giovanni Paolo; Puligheddu, Corrado; Chiasserini, Carla Fabiana; Trinchero, Daniele. - ELETTRONICO. - (2025). (IEEE ISCAS 2025 London (UK) 25 - 28 Maggio 2025) [10.1109/ISCAS56072.2025.11043906].

Availability:
This version is available at: 11583/3000440 since: 2025-06-30T10:33:54Z

Publisher:
IEEE

Published
DOI:10.1109/ISCAS56072.2025.11043906

(Article begins on next page)

LoRaWAN Architectures in the ISM2400 Band for AgriFood Applications

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***Abstract*—This paper evaluates the performance of LoRa technology operating in the ISM2400 band (2400-2483 MHz) in rural environments, focusing on its potential applications for precision agriculture. Sub-1 GHz bands like the EU868 and the US915 are already implemented for LoRa networks deployments, but the ISM2400 one may offer advantages with no duty cycle limitations and common regulatory prescriptions worldwide. However, the band faces challenges due to higher noise levels and reduced propagation performance through obstacles. For this reason, we have conducted some preliminary field tests, with results that demonstrate reliable communication in Line-of-Sight (LOS) over distances at least equal to 18 km with a Packet Delivery Ratio (PDR) of 100 %. We have also compared the obtained results in the EU868 band. Despite the limitations of the ISM2400 band, we highlight its potential for real-time, long-range, low-data-rate links, particularly suitable for agricultural applications such as autonomous farming vehicles control.**

***Index Terms*—Wireless Sensor Networks, LP-WAN, LoRa, Shared Spectrum Applications, IoT, Connectivity for Agriculture**

I. Introduction

LoRa (Long Range) [1] wireless technology has become a popular choice for Low-Power, Wide-Area Network (LP-WAN) applications [2], particularly in agricultural, as well as in industrial and smart city fields. By implementing Chirp Spread Spectrum (CSS) modulation, LoRa enables long-distance data transmission, while maintaining low energy consumption and enhanced robustness against interference.

Traditionally, LoRa operates in sub-1 GHz frequency bands, such as the EU868 (863-870 MHz) in Europe and the US915 (902-928 MHz) in North America, and supports low data rates, generally ranging from 0.3 kb/s to 5 kb/s in the EU868 band [3], making it suitable for sensor readings. Unfortunately, the use of sub-1 GHz bands is constrained by regulatory limitations, mainly in terms of duty cycle, with strong reinforcement in European countries. For instance, in the EU868 band, the LoRa uplink is limited to 1 % of the available time within an hour. This may introduce significant delays, hindering support for real-time applications. Furthermore, the sub-1 GHz bands cover different frequency ranges in different parts of the world, forcing manufacturers to design multiple hardware versions of the same product depending on the destination market.

To address these limitations, a possibility is represented by the adoption of wireless systems working in the ISM2400 band, with significant advantages, including the absence of regulatory duty cycle restrictions. This enables better latency, crucial for industrial automation and asset tracking applications but also important in agriculture, for all those scenarios that require real-time connection. As an added benefit, the ISM2400 band is common in any country worldwide and allows manufacturers and service providers to use standardized hardware.

On the other hand, the use of frequency bands above 1 GHz suffers from reduced propagation performance: the higher the frequency, the more susceptible propagation becomes to attenuation from physical obstructions such as buildings, trees or walls, with greater signal degradation over longer distances. This is only partially mitigated in the uplink by more favorable Effective Isotropic Radiated Power (EIRP) limits, which are at least 4 dB higher.

Additionally, the ISM2400 band is a shared and crowded spectrum, commonly used by several technologies like Wi-Fi [4], Bluetooth [5], ZigBee [6], RFID [7], and recently, LoRa [8]. The abundance of technologies sharing this same spectrum causes potential interference and congestion, which degrade the performance.

Among all, ZigBee and Bluetooth Low Energy (BLE) can be used for IoT applications, together with LoRa. ZigBee is better suited for indoor industrial environments, with limited propagation ranges up to 50 m. BLE is energetically efficient compared to any other solution, but it has been traditionally implemented over very short ranges. In a recent study, it has been shown that its radio enhancements enable trading off data rate for longer ranges, up to 450 m [9]. However, this extended range might still be inadequate for agricultural applications that require broader coverage, such as large-scale deployments across vast fields and remote areas.

The recent introduction of LoRa in the ISM2400 band offers an interesting alternative [10], [11], which has led many authors to explore LoRa's performance above 1 GHz, focusing on indoor settings [12], [13], in the presence of Wi-Fi activities [14], [15], or considering interferences with Bluetooth [16]

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of Next-GenerationEU, partnership on the Agritech National Research Center (NRRP – Mission 4 Component 2, Investment 1.4 – D.D. 1032 17/06/2022, CN00000022) and on "Telecommunications of the Future" (NRRP - Mission 4, Component 2, Investment 1.3, CUP E13C22001870001, PE00000001 - program "RESTART"). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

and LTE [17] in laboratory conditions. While several studies provide useful tools for the theoretical evaluation of LoRa in the ISM2400 band [18], [19], validation through field tests remains limited. Few papers have reported outdoor experimental measurements. For example, [20] found the longest reliable range to span 1.7 km to 2.5 km, whereas [21] analyzed the performance over a lake. Another study [22] estimated maximum communication distances in metropolitan and urban environments using propagation models.

This paper presents results from an extended field test experiment, that involved the deployment of LoRa ISM2400 devices configured in a LoRaWAN network using The Things Network (TTN) infrastructure [23] to collect data about signal and system performance.

II. Methodology

The physical layer of LoRa in the ISM2400 band was proposed by Semtech, with the project not yet supported by the LoRa Alliance. For the radio, we selected the Semtech SX1280 RF module, which supports four different channel bandwidths, 203 kHz, 406 kHz, 812 kHz and 1625 kHz, with Spreading Factors (SFs) ranging from SF5 to SF12. Theoretically, the position and number of network channels can be chosen by the network operator; since we opted for TTN, we followed the system frequency plan ISM 2400 3CH DRAFT2, which introduces three specific channels at frequencies 2.403 GHz, 2.425 GHz and 2.479 GHz.

A. Hardware Setup

For the gateway, we used a Rapsberry Pi model 4 mini-PC mounting a LoRa board manufactured by Semtech, model SX1280Z3SDFGW1. The LoRa radio was connected to a monopole antenna with a gain of 1.5 dBi. The Raspberry Pi was connected to the Internet via a MikroTik RB750UPr2 hEx PoE lite router, equipped with a 4G dongle.

As an end-node, we used the STMicroelectronics NUCLEO-L073RZ development board, mounted with a Semtech SX1280ED1ZHP LoRa shield that features on-board printed antennas with an estimated gain of 1.5 dBi.

B. Geographical Setup

Outdoor tests were carried out in a rural area located in the Piedmont region of Italy, specifically the Verrua Savoia Fortress, which sits at an elevation of 287 m above sea level with surrounding flat areas from 120 to 239 m above sea level. The site overlooks the Po Valley, providing extended optical visibility from the city of Torino (50 km to the west) to Milano (100 km to the east), as shown in Fig. 1.

This location allowed the realization of long-range field tests, with the gateways exposed to interferences from the whole neighboring region and the end-nodes deployed in test sites at increasing distances, while constantly maintaining clear Line-of-Sight (LOS) between them. Figure 2 illustrates the field measurement setup, with both the gateway and the end nodes arranged on wooden dielectric tripods. Potential test sites were vetted on a map in a preparatory phase. The approach ensured that the chosen locations would satisfy the key requirement of clear LOS and also boosted the confidence in their field characterization, which was performed relying on a Global Navigation Satellite System (GNSS) receiver.

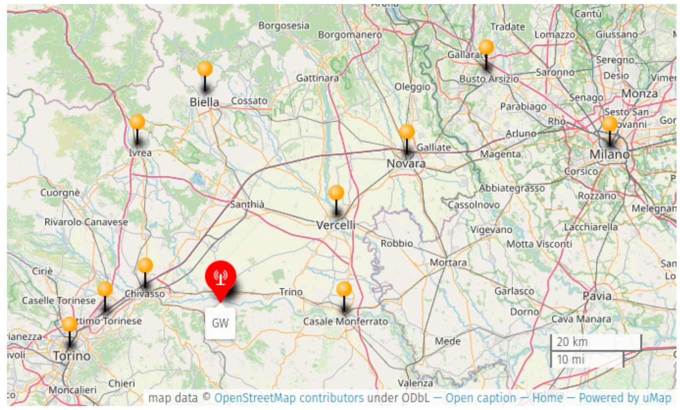


Fig. 1. Map of the area interested by the experiment. The red marker identifies the position of the gateways, overlooking the Po Valley with several large cities (above 50,000 inhabitants) within 100 km (orange markers).

(a) Gateway (b) End-nodes

Fig. 2. Devices deployment

C. Experimental Setup

The tests aimed to determine the range and reliability of the signal received by the gateway, focusing on key performance metrics like Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR) and Packet Delivery Ratio (PDR).

Initially, we configured our system to investigate transmissions on different channels at the maximum spreading factor, SF12 (Field Test I). After determining the best-performing one, we arranged a second test to use this fixed channel, but varying the spreading factor (Field Test II). The details of both experiments are provided in the following paragraphs and are summarized in Table I.

a) Field Test I: Initially, two end-nodes transmitted an uplink every 60 s, with RF output power set to 12.5 dBm. The bandwidth was set to 812 kHz, and the code rate to 4/8. With a payload length of 4 B and spreading factor SF12, the Time on Air (ToA) is 127.29 ms [24]. One end-node was configured

TABLE I
PARAMETER SETTINGS OF END-NODES

Parameter	Field Test I	Field Test II
Spreading Factor (SF)	SF12	SF11, SF12
Bandwidth	812 kHz	812 kHz
Code Rate	4/8	4/8
Payload Length	4 B	4 B
Time on Air	127.29 ms	127.29 ms (SF12) 63.64 ms (SF11)
Effective Data Rate	1.9042 kb/s	1.9042 kb/s (SF12) 3.4912 kb/s (SF11)
Frequency Channels	2.403 MHz	2.403 MHz
RF Output Power	12.5 dBm	12.5 dBm
Transmission Interval	60 s	60 s (30 s delay between nodes)

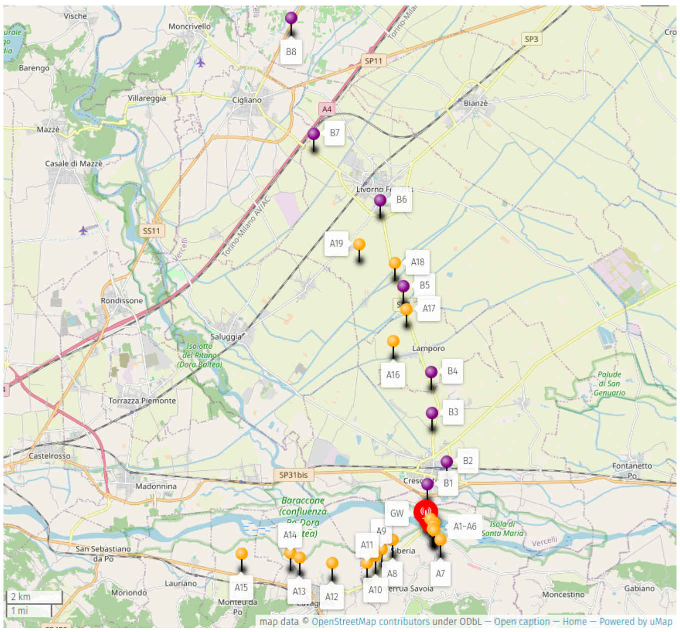
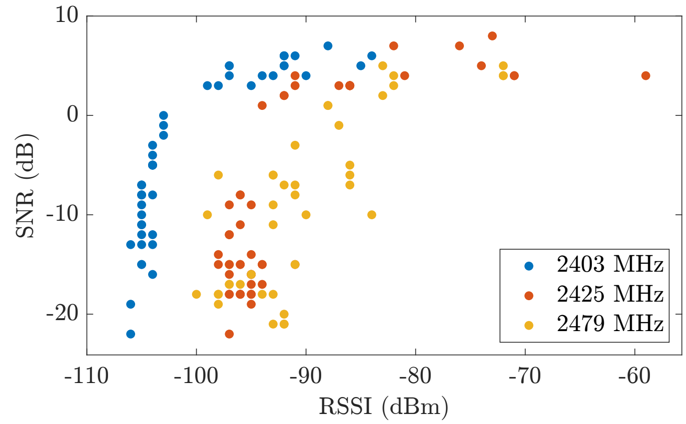


Fig. 3. Locations of the end-nodes during Field Test I (orange markers) and Field Test II (purple markers). The gateways' position is indicated by the red marker.

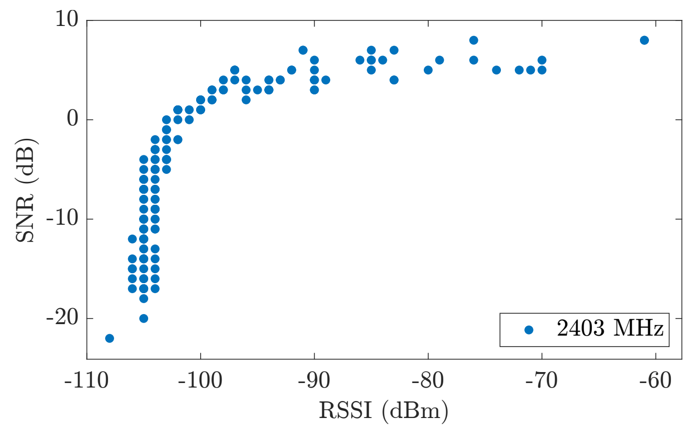
to transmit exclusively on channel 1 (2.403 MHz), while the other made use of all three channels (2.403 MHz, 2.425 MHz and 2.479 MHz) randomly. The end-nodes were positioned at increasing distance from the gateway, from position A1 to A19, in different directions as shown in Fig. 3 with orange markers.

b) Field Test II: After identifying the best-performing channel, we focused on comparing LoRa performance by varying the spreading factor. A second gateway was installed near the first one and configured with spreading factor SF11, while the first gateway continued operating with SF12.

Accordingly, the two end-nodes were set to transmit in the frequency channel 2.403 MHz, with spreading factors SF11 and SF12, respectively, and a 30 s delay to avoid mutual interference. In this phase, a different direction in the valley was explored, from position B1 to B8, as shown with purple markers in Fig. 3.



(a) End-node randomly transmitting on all three channels



(b) End-node transmitting exclusively on channel 1

Fig. 4. Field Test I results. SNR versus RSSI maps. Both end-nodes transmit with 12.5 dBm RF output power and spreading factor SF12.

D. Data Acquisition

Uplink packets from end-nodes were published to dedicated MQTT topics, leveraging the integration exposed by the network server of The Things Network infrastructure. A Python script was developed to act as a subscriber through the Eclipse Paho client, receiving and logging message payloads for real-time monitoring of communication performance, in addition to preprocessing the data for subsequent statistical analysis. For each message, key fields including the RSSI, the SNR, and the end-node uplink counter were extracted. This setup enabled the calculation of the PDR on the fly, by maintaining a sliding window of recent uplink counter values and searching for gaps that indicated lost packets, while also facilitating data exchange for visualization in the MATLAB environment.

III. RESULTS AND DISCUSSION

The results obtained during Field Test I are collected in Fig. 4, where for each measurement we represent the RSSI paired with the SNR. In Fig. 4a, it is clear that only channel 1 allows us to test the performance over longer range, as channels 2 and 3 are significantly limited by the presence of stronger interference. Even if the connection is established and the link is maintained 20 dB below the noise level, the

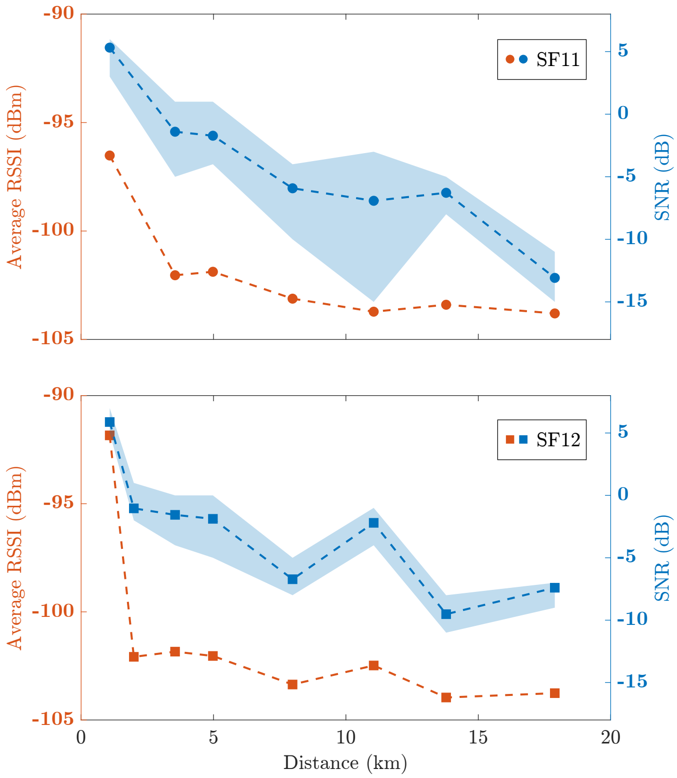


Fig. 5. Field Test II results. Average RSSI and SNR versus distance, for spreading factors SF11 and SF12 on channel 1. The light blue bands display the dispersion of SNR measurement results.

presence of stronger interference limits reception to higher values of RSSI, thereby reducing the maximum distance. On the contrary, with channel 1, we obtained connections with RSSI down to −110 dBm and SNR down to −20 dB, as highlighted in Fig. 4b. For this reason, Field Test II was run only on channel 1.

The results of our tests indicate that we successfully transmitted data from the end-node to the gateway over a distance ranging from 1 km to 18 km. Farther positions were not tested, but preliminary investigations showed the possibility to reach even longer distances. All of these long-range transmissions achieved a PDR of 100 %. The performance metrics are illustrated in Fig. 5, where we represent, as a function of the distance between the gateway and the end-node, the average RSSI and the range of SNR values measured at each test site.

IV. Conclusions

In conclusion, our experimental results demonstrate the possibilities offered by LoRa technology operating in the ISM2400 band for long-range communication in agricultural applications requiring real-time transmissions, compared to traditional IoT applications exploiting sub-1 GHz LoRa. The successful transmission of data up to 18 km with zero packet loss underscores the potential of this technology.

As a reference, we compared the obtained results to achievements obtained over the years in the EU868 band, taking data from a project with 150 LoRaWAN gateways deployed in several Italian regions and more than 300 nodes connected at various distances [25]. Among all, we selected a long distance link (67.4 km) with an average PDR over the years equal to 98 % for 144 transmissions per day. Clearly, the achievable distance in the EU868 band is much longer, but the preliminary results in the ISM2400 band appear very promising. As a direction for future work, we plan to explore additional configurations and longer distances. This comprehensive analysis will allow us to further optimize the performance of LoRa devices, ensuring reliable communication in diverse agricultural scenarios.

Acknowledgment

The authors thank Mrs. Anita Direnzo for her collaboration during the logistic phase of the field tests.

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